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SCALING EFFECTS IN DROP TESTS ON IFTC MODELS

Report No. 88-275-K

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ABSTRACT

In the course of the development and licensing of the Irradiated Fuel Transportation Cask, two series of drop test experiments were carried out, with two different sizes of scale models of the cask ($1/7^{th}$ and 1/2 scale). This report reviews the results of these tests, with particular emphasis on the scalability of results. The small scale model tests provided very good qualitative predictions of the structural response of the larger model. Such discrepancies that did arise can be largely attributed to small changes in the test conditions and differences in the methods used to fabricate the different size models. It is concluded that scale model testing can be a very effective, low-cost way of predicting the performance of large, expensive pieces of equipment under impact loading conditions.

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To Mr. H.N. Isaac
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SCALING EFFECTS IN DROP TESTS ON IFTC MODELS

1.0 INTRODUCTION

Scale model testing can be an extremely useful way of prediction the structural response of an engineering design when testing of the full-scale prototype is impractical. However, for a variety of theoretical and practical reasons, it is not always possible to reproduce all structural features and loading conditions exactly at reduced scale. Experimental design will generally entail compromises and approximations. The objective, of course, is to get the most reliable results possible, given the inevitable cost and time constraints. This requires theoretical insight and good practical judgment.

This report reviews the results of two series of scale model tests carried out during development and licensing of the Irradiated Fuel Transportation Cask (IFTC). The tests, which featured a series of nine metre drops onto a flat, unyielding surface, were substantially repeated at two different scales ($1/7^{th}$ and 1/2 full size). This provided an opportunity to examine the effects of scale on this type of experiment.

2.0 BACKGROUND

The Irradiated Fuel Transportation Cask was designed by the Nuclear Material Management Department (NMMD) for the transportation of two standard modules of irradiated fuel (196 bundles) on public highways. The Atomic Energy Control Board requires proof that this type of package (classified as a Type B(U) package) is capable of surviving a variety of accidental loading conditions, including/1/:

- A nine metre drop onto an unyielding surface, with the cask orientated so that the drop causes the maximum possible damage;
- A one metre drop onto a vertical cylindrical steel bar, 15 cm in diameter and at least 20 cm long, again with the package orientated for the maximum damage;
- A thermal (fire) test in which the entire package is subjected to heating at at least 800°C for 30 minutes.

Part of the licensing application for the Irradiated Fuel Transportation Cask (IFTC) was based on a series of demonstration drop tests, carried out with scale models of the package. These tests showed that the design could survive the impact loads arising from the AECB mandated 9 metre and one-metre drops without suffering damage to cask integrity or shielding. In the course of the testing, measurements were made of the impact accelerations and of the response of the cask to these dynamic loads.

The application to license the IFTC for road use was organized by NMMD, with Mechanical Research Department providing support in the area of test design and test program administration. Drop tests were conducted at AECL/CRNL, while the thermal tests were carried out at the National Research Council's facilities in Ottawa.

Licensing impact tests were carried out on a fully detailed half-scale model of the cask. The reason for using a half-scale model were chiefly economic. The model was less expensive to build than a full scale prototype, handling was much easier and, because the weight of the model was one-eighth the weight of a full scale cask, it was possible to carry out the drop tests at AECL's Chalk River Laboratories (the nearest facility capable of handling the full forty tonne cask was at Oak Ridge Tennessee.)

Rather than argue a rationale for a single "worst case" drop orientation, the licensing test plan proposed a series of 5 drops, three from 9 metres and two from one metre onto a cylindrical "spike".

Before the half-scale licensing tests were attempted, two series of tests were conducted with seventh-scale models of the cask. These tests were aimed at checking out test procedures and at establishing that the design of the cask, especially the lid bolts, seals and impact limiter, was adequate. As these tests were intended to provide design information, the models were instrumented with accelerometers and strain gauges.

The seventh-scale tests provided very useful information on the need to strengthen the impact limiter tie-down arrangement. They also reassured the Hydro team that the cask could survive multiple drop tests without serious damage.

The use of half-scale models for the licensing tests was justified on the basis of scaling theory and reference to other impact tests that indicated that half-scale tests would accurately predict the behaviour of a full scale cask. No explicit reference was made to the seventh-scale tests in the Safety Analysis Report.

3.0 SCALING PRINCIPLES

Scaling theory is discussed in more detail in Appendix A. The highlights are:

- The model must be an exact scale replica of the full-scale (prototype) object. Thus:

$$l_m = s.l_p$$

where:

l_m is any linear dimension on the model;
l_p is the equivalent dimension on the prototype; and
s is the scale factor.

- It is theoretically possible to build models from different materials, but scale model testing is much more practical if material behaviour is identical in model and prototype. Thus:

$$\sigma_m = \sigma_p \quad \text{(stress)}$$
$$\epsilon_m = \epsilon_p \quad \text{(strain)}$$

- If the same material is used for the prototype and the model, then to achieve the same stress levels (including the same degree of plastic deformation), it is necessary to have the same **energy density** at both scales.

- The impact velocity will have to be the same for the model as for the prototype.

$$v_m = v_p$$

- Time will be compressed in the small scale model. Impact duration is theoretically smaller by the scale factor:

$$t_m = s.t_p$$

- Because strain levels are the same in model and prototype, but time is scaled, **strain rates** will be higher in the smaller version:

$$m = \frac{1}{s} \cdot p$$

- Accelerations will also be higher in the smaller scale model:

$$x_m = \frac{1}{s} \cdot x_p$$

4.0 THE SCALE MODELS

4.1 Half-Scale Model

As mentioned previously, the half-scale model was a fully detailed scale replica of the IFTC design. (Figure 1 shows the main features of the cask design.) All dimensions, including length, breadth and height, wall thicknesses, clearances and thread sizes were carefully reproduced in half-scale. The cask material was type 304L stainless steel, like the prototype and the fabrication method - welding of rolled plate - was identical to the method proposed for the service casks. The lid bolts were made from a special Nitronic 60 stainless steel alloy chosen for superior anti-galling properties. All seals, including the lid, vent and drain were detailed scale replicas. The bronze vent and drain covers were modeled from the full scale design.

The impact limiter was also a carefully scaled replica of the design proposed for the road-going IFTC's. The core material was redwood. Since redwood is strongest parallel to its grain, the limiter was made up of a large number of blocks, all aligned so that the grain was perpendicular to the local surface of the skin. The outer skin was welded stainless steel sheet.

4.2 Seventh-Scale Model

The seventh-scale models (two were eventually fabricated) were designed to provide general information on the response of the cask design to drop test impacts. In the interest of economy and time savings, the design was simplified in several areas:

- Drain and lid vent ports were eliminated (although there were simple ports for pressurizing the model before tests and monitoring pressures after the drop).

- The complicated "dove-tail" profile of the lid seal in the IFTC design was simplified into a standard O-ring groove. The cross section diameter of the lid seals was close to 1/7th that of the full scale seal; indeed the model scale ratio was chosen to allow us to match scale with standard O-ring material.
- Lid bolts were based on standard 5/16 - 24 UNF stainless steel bolts. These had a diameter of 7.94mm and a thread pitch of 1.06mm. By comparison, the full scale bolts are specified as M56 x 5.5 (56mm diameter, 5.5mm thread pitch) and are to be made of Nitronic 60 stainless steel. The bolts for the seventh-scale model were machined down at the shank so that the ultimate strength of the bolts was 1/49th the predicted strength of the full scale bolts.
- The cask bodies were machined from a Type 304L stainless steel casting. This, as it turned out, led to a considerable discrepancy between material properties in the half- and seventh-scale models. The cast material had a very coarse grain structure and a relatively low yield stress, compared to the rolled plate used for the half-scale model. The seventh-scale lids were machined from rolled plate, later identified as type 430F free-cutting stainless steel. (Figure 2 compares the stress/strain curves for cast and rolled materials used in the seventh-scale models.)
- Impact limiters were close replicas of the full scale design, but naturally it was not possible to scale grain size in the wood (although one of the designers who participated in the test program suggested that timber from stunted trees might be procured).

Both the half- and seventh-scale models were loaded with a simulated "payload" for the drop tests. In both cases, this consisted of an assembly of steel plates, separated by washers and bolted together with threaded rods. These were designed be equivalent in weight to a full load of fuel (complete with modules) and to fit inside the cask cavities with only nominal clearance. The objective of this design was to simulate the structure and weight distribution inside the cask at a reasonable cost.

5.0 TEST PLAN

5.1 Instrumentation and Measurements

The half-scale drop tests were designed mainly as proof tests - tests that would show whether or not the IFTC design would survive the drop tests without allowing radioactive material escape to the environment. For the IFTC, leakage past one of the seals (especially the lid seal) was the most plausible mode of failure. For this reason, the most important part of the post-drop inspection were leak tests, carried out with very sensitive helium mass-spectrometer leak detection equipment.

Since the pass/fail criterion depended entirely on the post-test condition of the cask, there was no formal license-related requirement for measuring accelerations and loads during the tests. However, at the time that the tests where being planned, it was not obvious that the cask would survive all of the tests on the first attempt. Extra instrumentation was installed to provide informations that might be useful if the package had to be redesigned. This included:

- six accelerometers mounted on the cask body on two triaxial mounting blocks; (These were small steel cubes, drilled and tapped so that three accelerometers could be mounted on each, with their axes aligned in mutually perpendicular directions.)
- a seventh accelerometer mounted at the centre of the lid;
- several strain-gauged lid bolts; and
- several strain gauges. mounted in various locations on the lid and cask body.

The instrumentation on the half- and seventh-scale models was similar, though different in detail. Figures 3 and 4 show the location the the instruments on the models.

Measurements of the gap between the lid and the cask body and of lid bolt torques were taken before and after the drops.

5.2 Seventh-Scale Tests: Drop Sequence

Two series of tests were carried out on seventh-scale models. During the first series (September 23-25, 1985) a model was dropped six times, in the orientations shown in Figure 5:

- Drop 1 was on a bottom corner. The impact limiter was not fitted over the lid for this test.
- Drop 2 was on a top corner, with the impact limiter in place.
- Drop 3 had the cask model in an upright orientation, with a thin impact limiter on the bottom (at the time of the test, there was concern that a flat bottom-down drop would lead to unacceptably high acceleration loads.)
- Drop 4 was a repeat of drop 3, but with no bottom impact limiter.
- Drop 5 was on a top edge.
- Drop 6 was again on a bottom corner (like Drop 1). The full impact limiter was used for this test.

A major finding of these tests was that the bolts fastening the impact limiter to the cask lid were inadequate. While we were able to arrange a temporary tie-down arrangement and complete the planned test program, it was clear that a re-design of this detail was necessary. The second series of tests (December 3-5, 1985) focused on confirming that the re-designed limiter tie-down bolts were adequate so that there was no dynamic instrumentation on the cask.

5.3 Half-Scale Tests: Drop Sequence

There were also two series of drop tests carried out with the half-scale model.

The first series (March 26 - April 16, 1986) comprised five drops, as shown in Figure 6. These were:

- Drop 1, onto a bottom corner, form 9 metres.
- Drop 2, onto a top corner (with the impact limiter in place), from 9 metres.
- Drop 3, onto the same corner as drop 2, from one metre above the top of the cylindrical spike.
- Drop 4, a flat bottom drop from 9 metres.
- Drop 5, a side drop from one metre, arranged so that the top of the spike would hit the cover of the drainage port.

The second series of drops were carried out no May 15, 1986. These included:

- Drop 6, a side drop form 9 metres, aligned so that one of the lifting trunnions was the first part of the cask body to strike the target plate.
- Drop 7, a drop onto the top corner from 9 metres.

For clarity, these tests will be referred to drops 7-1 through 7-6 and 2-1 through 2-7. Direct comparison of test results is possible for:

- drop 7-1 vs. drop 2-1 (bottom corner)
- drop 7-2 vs. drop 2-2 and 2-7 (top corner)
- drop 7-4 vs. drop 2-4 (flat bottom)

6.0 TEST RESULTS

6.1 Anticipated Scaling Effects

The seventh-scale model is approximately a 1/3.5 scale replica of the half-scale model. According to scaling theory then, for the same test set-up, we would anticipate:

- deformation patterns (including degree of crushing) should be the same in both scales;
- stresses and strains should be the same.
- acceleration levels would be 3.5 times higher for the seventh-scale models; and
- time durations (including period of vibration) would be 3.5 times longer for the half-scale model.

6.2 Bottom Corner Tests

6.2.1 Qualitative Results:

There was a noticeable degree of plastic deformation on the bottom corners of the casks where the impact occurred. For the half-scale model, the deformation pattern was very symmetrical, indicating that the model fell squarely, with the centre of gravity above the centre of impact (Figure 7). The seventh-scale model tumbled somewhat in the air, with the result that the impact area extended along one of the edges (Figure 8). The "footprint" of the squashed corner was larger (in proportion) for the seventh-scale model and there was evidence of considerable plastic deformation in the adjacent material (Figure 9). We attribute this to the lower yield strength of the cast material of the smaller model.

The first of the seventh-scale tests was done without a wood-core impact limiter in place - instead a steel plate of equivalent weight was mounted on the lid. This arrangement was used to avoid damaging the limiter before it was needed for the top corner test. Unfortunately, this strategy resulted in damage of the cask model that should have been avoided:

- On impact, the bolts holding the steel plate broke and the plate slid across the top of the lid, shearing off three lid bolts and damaging several others.
- The cask (now without any protection in the lid area) bounced after the first impact and came down on a top corner. This caused further damage to the lid.

Following the drop tests, each cask was leak tested and disassembled for inspection. The half-scale model showed virtually no damage in the lid area and passed all leak tests. The seventh-scale model was more seriously damaged. Bolts were sheared and there was evidence of plastic deformation near two top inside corners of the cask body, apparently caused by impact of the lid against the inner edge of the cask body. The lid seal was not leak tight. However, for the reasons cited above we believe that much of the damage was the result of poor test design and differences in material properties, not due to the difference in scale.

6.2.2 Quantitative Results:

Figures 10 through 13 compare accelerometer traces from tests 7-1 and 2-1. Figure 10, labeled "vertical component" has traces from the accelerometers mounted vertically on the cask. (During the drop, the these accelerometers would be inclined at about 35° to "earth" vertical.) Figure 11, labeled "longitudinal component" refers to accelerometers mounted parallel to the long edge of the cask while Figure 12, labeled "transverse component" refers to accelerometers mounted perpendicular to the long face. Figure 13 compares accelerometer traces for instruments mounted at the centre of the lid in a vertical orientation. As was mentioned earlier, there were a total of six accelerometers on the cask body, mounted in sets of three on opposite corners. The traces shown in the figures were generally obtained by averaging the results from the two blocks. Where an accelerometer record was unobtainable, due to transducer or cable failure, the trace from the survivor is presented by itself. Peak accelerations and impact durations for each of the traces are summarized in Table 1.

Table 1

Drop 1: Bottom Corner Impact

Accelerometer Mounting	Seventh-Scale Peak Accel. (g)	Seventh-Scale Duration (msec)	Half-Scale Peak Accel. (g)	Half-Scale Duration (msec)
Vertical	1830	2.6	230	10.6
Longitudinal	1670	2.4	525	13.7
Transverse	875	2.1	420	12.1
Lid	not available			

The impacts are obviously shorter and sharper for the seventh-scale model. The difference more than 3.5 times for the vertical component and less than 3.5 for the transverse component. Moreover, the impact duration is shorter by a factor of more than 1/3.5. These results are consistent with the observation that the models hit the target with slightly different orientations. The half-scale model landed almost directly on its corner and the highest accelerations were measured parallel to its long axis. The smaller model rotated during its fall so that its lower surface was somewhat closer to horizontal - hence the higher "vertical" component of acceleration. The larger "footprint" of the seventh-scale test is consistent with a more abrupt impact.

The lid bolts on the half-scale model lost (on average) 34% of their initial torque while the lid gap increased by an average of 0.01 mm. For the seventh-scale model, the loss in bolt torque was 38% (for the bolts that were not sheared off) while the average increase in gap was 0.02 mm. The substantially larger gap increase for the seventh-scale model was likely caused by a secondary impact when the cask came down on an unprotected top corner.

6.3 Top Corner Tests

6.3.1 Qualitative Results:

The seventh-scale model fell squarely on its top corner, resulting in a triangular "footprint" that extended almost half of the way along the top edges and along the entire side edge of the limiter (Figure 14). The skin of the limiter was flattened over the area of the footprint, but there was no tearing, except for some limited cracks around the lifting hook recess. The first limiter tested separated from the cask during the test and a new design was developed with more larger tie-down bolts. This design was subsequently tested and found to work well.

There were two top corner tests on half-scale models (tests 2-2 and 2-7). During the first (Test 2-2, April 2) the seams on the edges of the limiter split open, exposing the wooden core and allowing some of the shattered redwood to escape. This was attributed to poor quality welds and a second limiter was fabricated. When the cask was tested with this limiter (Test 2-7, May 15), all seams remained intact (except for limited tearing around the lifting hook recess). In all respects, the deformation pattern strongly resembled the pattern observed on the seventh-scale limiter. (See Figures 15 and 16)

There was no discernible damage to the seventh-scale model cask or lid as a result of the top corner drop. When the half-scale model was tested with the limiter that split open, the corner of the cask came into contact with the target plate and there was minor damage. This did not occur with the half-scale model when the better quality limiter was used.

6.3.2 Quantitative Results:

Figures 17 through 19 show accelerometer traces from two of the top corner drops (September 24, 1985 and April 2, 1986) Instrumentation was not used in the other top corner tests. The peak accelerations and impact durations are summarized in Table 2.

Table 2

Drop 2: Top Corner Impact

Accelerometer Mounting	Seventh-Scale Peak Accel. (g)	Seventh-Scale Duration (msec)	Half-Scale Peak Accel. (g)	Half-Scale Duration (msec)
Vertical	210	21	72	43.
Longitudinal	165	n/a	93	40.
Transverse	260	20	75	41
Lid	not available			

The difference in peak acceleration is in the "ballpark" of being three and a half times higher for the seventh-scale model. However, it should be noted that the accelerometer records from the half-scale tests were extremely "noisy" so that it was very difficult to determine the beginning and end of events precisely. We believe that the noise in the signal has two origins: a lack of rigidity in the accelerometer mounts and inadequate sensitivity in the accelerometers. The accelerometers used in these tests were designed to withstand high shock loads, and had relatively low output for accelerations in the 100 g range. This meant that the gain on the signal conditioning amplifiers had to be turned up high, which emphasized background noise in the signals.

For the half-scale model, average bolt torques decreased by 48% and the average lid gap increased by .01 mm after a combination of the 9 metre drop and a 1 metre drop onto a cylindrical pin on the damaged corner. The seventh-scale test - a single 9 metre drop - resulted in a 64% decrease in average bolt torque and a 0.01 mm increase in lid gap.

6.4 Flat Bottom Drops

6.4.1 Qualitative Results:

Direct impact between the flat bottom of the cask and the target plate causes very high impact accelerations and it was anticipated that these g-loads could damage the lid and lid bolts. It was found that the lid made a noticeable impression on the cask body of the seventh-scale model, and a less obvious mark on the body of the half-scale model. This is consistent with our observations about the relative yield strength and hardness of the materials. Significant changes in bolt torques indicated some bolt stretching at both scales

6.4.2 Quantitative Results:

Figure 20 shows accelerometer traces from both the half-scale and seventh-scale flat bottom drop tests. The two traces for each scale represent the accelerations at two opposite corners of the models.

The two accelerometer traces are similar for the seventh scale test. This suggests that the instruments experienced accelerations of similar magnitude and duration. However, one of the traces, marked "A" on Figure 20, is delayed by about 0.0005 seconds compared to trace B. This suggests that one corner struck slightly sooner than the other. There is a more noticeable difference between the two traces for the accelerometers attached to the half scale model. In this case, trace B starts later, and lasts longer than trace A. This would be consistent with an impact situation where one corner hit slightly in advance of the other. The time difference between the two traces was approximately 0.003 second, which would imply a tilt of about 2^{o}. If the accelerometer traces are averaged for each test (which provides a measure of the acceleration at the centre of the model), then the accelerations and impact durations are as shown in Table 3 and Figure 21. Traces from the accelerometers mounted at the centres of the lids are shown in Figure 22.

Table 3

Drop 2: Top Corner Impact

Accelerometer Mounting	Seventh-Scale Peak Accel. (g)	Seventh-Scale Duration (msec)	Half-Scale Peak Accel. (g)	Half-Scale Duration (msec)
Vertical	1936	1.8	881	4.9
Lid	1816	1.6	989	n/a

6.5 Leak Rate Test Results

Leakage rates for the lid seals were measured in the same way for both sizes of model. The interior of the cask was pressurized to 100 psi with a mixture of nitrogen (85%) and helium (15%). A highly sensitive helium mass-spectrometer leak testing instrument was connected to the small space between the inner and outer O-ring seals and the interseal space was evacuated by a vacuum pump connected to the leak tester. Any helium leaking past the inner O-ring seal was drawn through the leak tester.

Lid seal leakage rates for the seventh-scale model varied between 2.6×10^{-6} and 1.3×10^{-5}. Lid seal leakage for the half scale mode were between 8×10^{-5} and 4×10^{-4}.

We hesitate to attach much significance to these figures because of our wider experience with leak testing. We have observed that measure leak rates are extremely sensitive to very small changes in O-ring condition and history, and the quality of surface finish on the steel sealing faces. Further work would be required to accurately quantify the relationship between scale and leak rate.

7.0 CONCLUSIONS

The impact experiments carried out with two different scales of models yielded qualitatively similar results. The nature and extent of local deformation at the point of impact was consistent for both the cask components and the impact limiter. Some elements of damage, especially bolt stretching and lid gap increases tended to be more severe in the smaller models. However, much of the difference can be attributed to differences in material properties (especially the lower yield strength of the cast steel) or small geometrical differences (the bolt threads were relatively coarser for the small models).

Measured accelerations were higher for the small models, as predicted by scaling theory. Likewise, impact durations were shorter for the small model.

We conclude that scale model testing can be an effective, low-cost way of predicting the performance of large, expensive pieces of equipment. The reliability of the prediction depends on the quality of the model and on the scaling ratio. We are confident that the half scale model gave reliable results for the license tests because it was an extremely accurate model, with a modest (2:1) scale ratio.

8.0 ACKNOWLEDGMENTS

The work reported here reflects the efforts of many individuals and groups. We wish to particularly recognize the role of Mr. K.E. Nash, who served as project engineer on the IFTC project during the period of the licensing tests. AECL staff who played an important part in the testing include Mr. Daniel Beaulieu, test engineer and Mr. John Trompe, who did an excellent job with the instrumentation. Messrs. John Russell, Alan Fallis and Roberto Zane of the Mechanical Research Division played essential roles in preparing for the testing.

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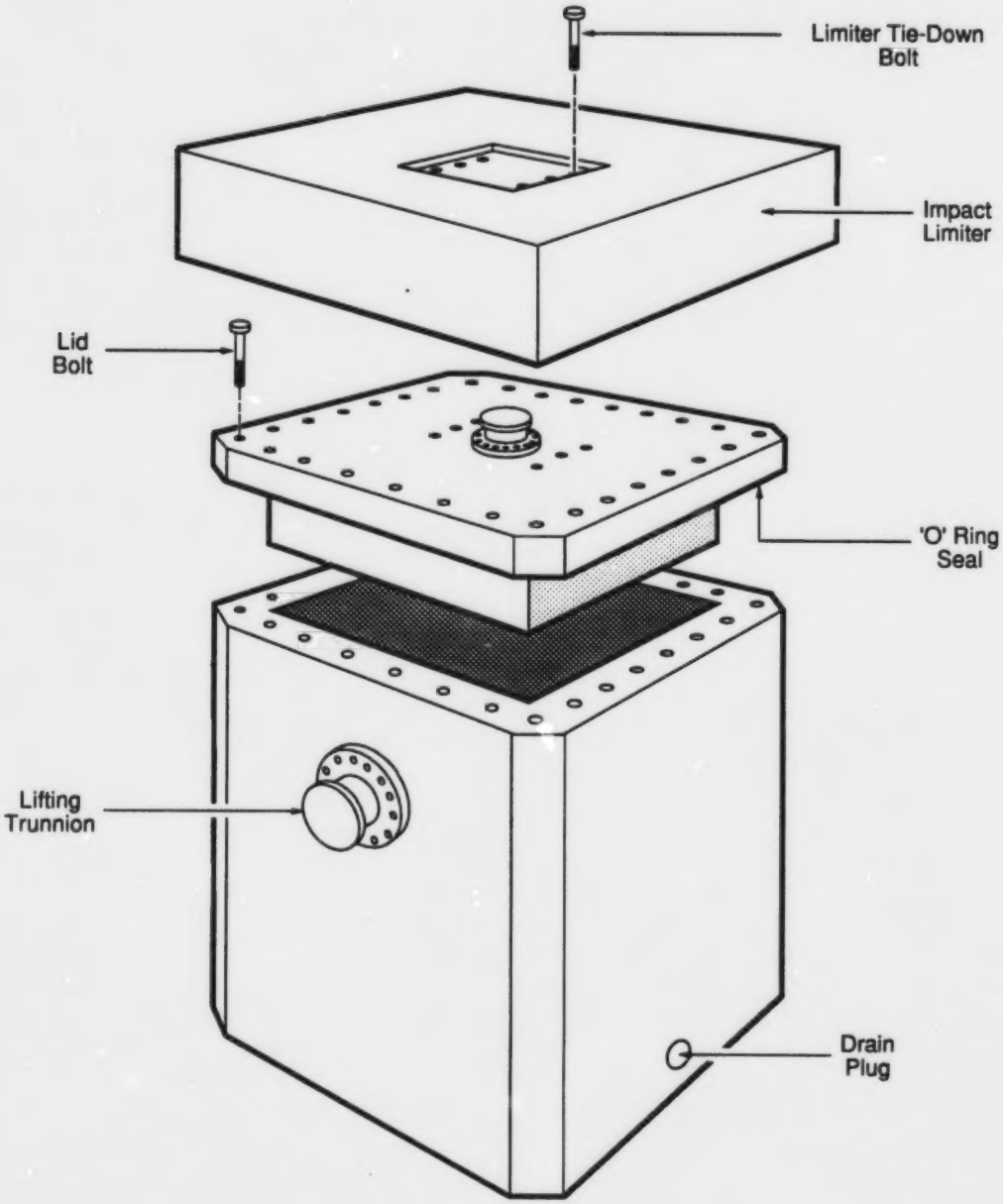

FIGURE 1

GENERAL FEATURES OF THE IFTC

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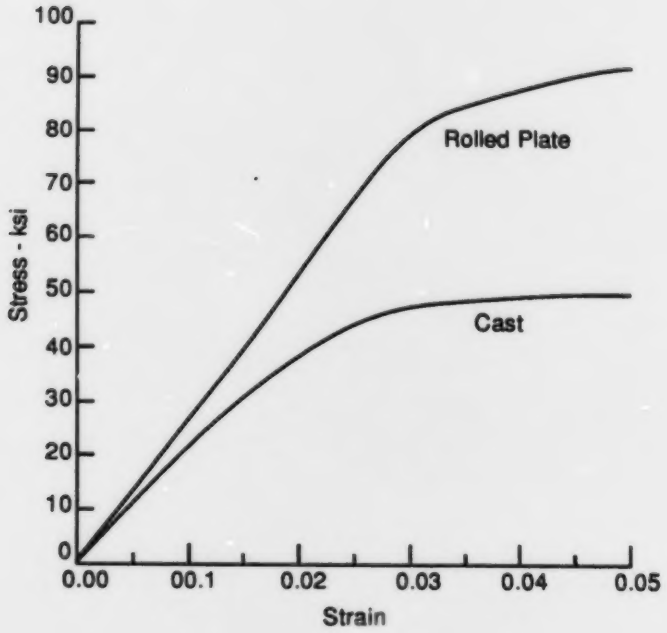

FIGURE 2

COMPARISON OF MATERIAL PROPERTIES FOR CAST AND ROLLED STAINLESS STEEL

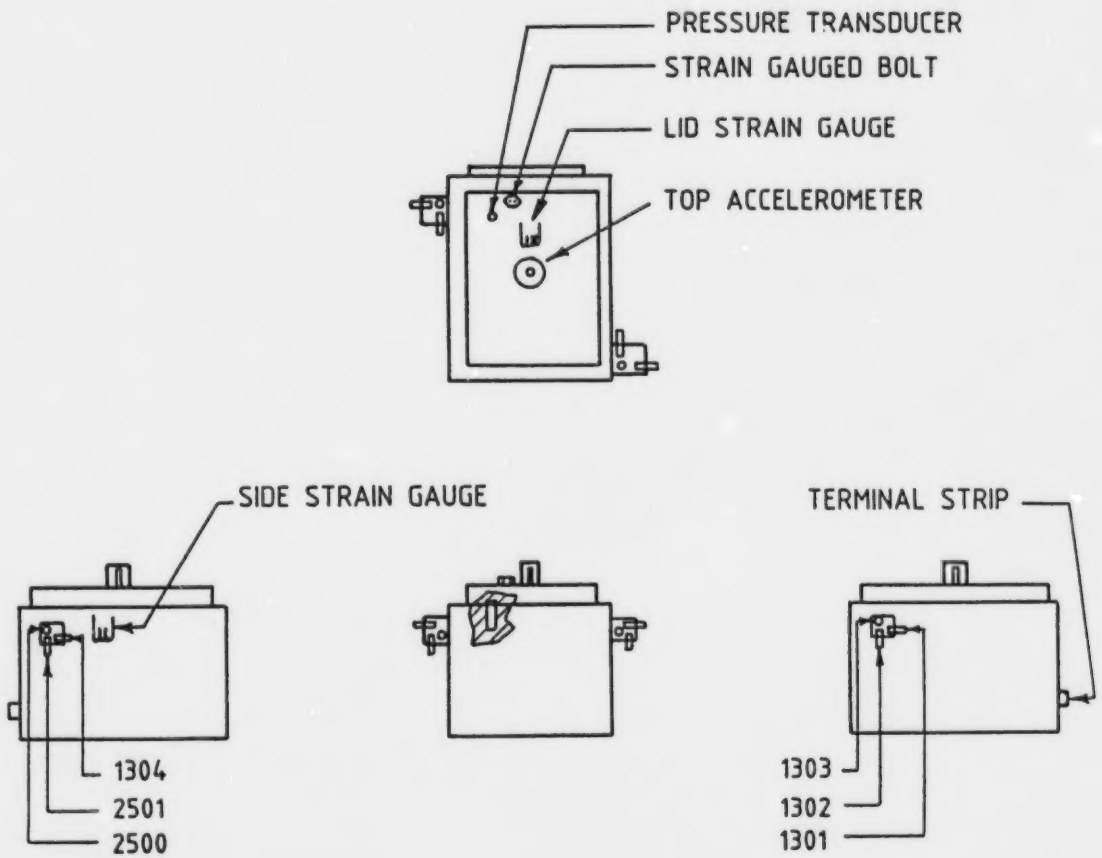

FIGURE 3
INSTRUMENT PLACEMENT ON SEVENTH SCALE MODEL

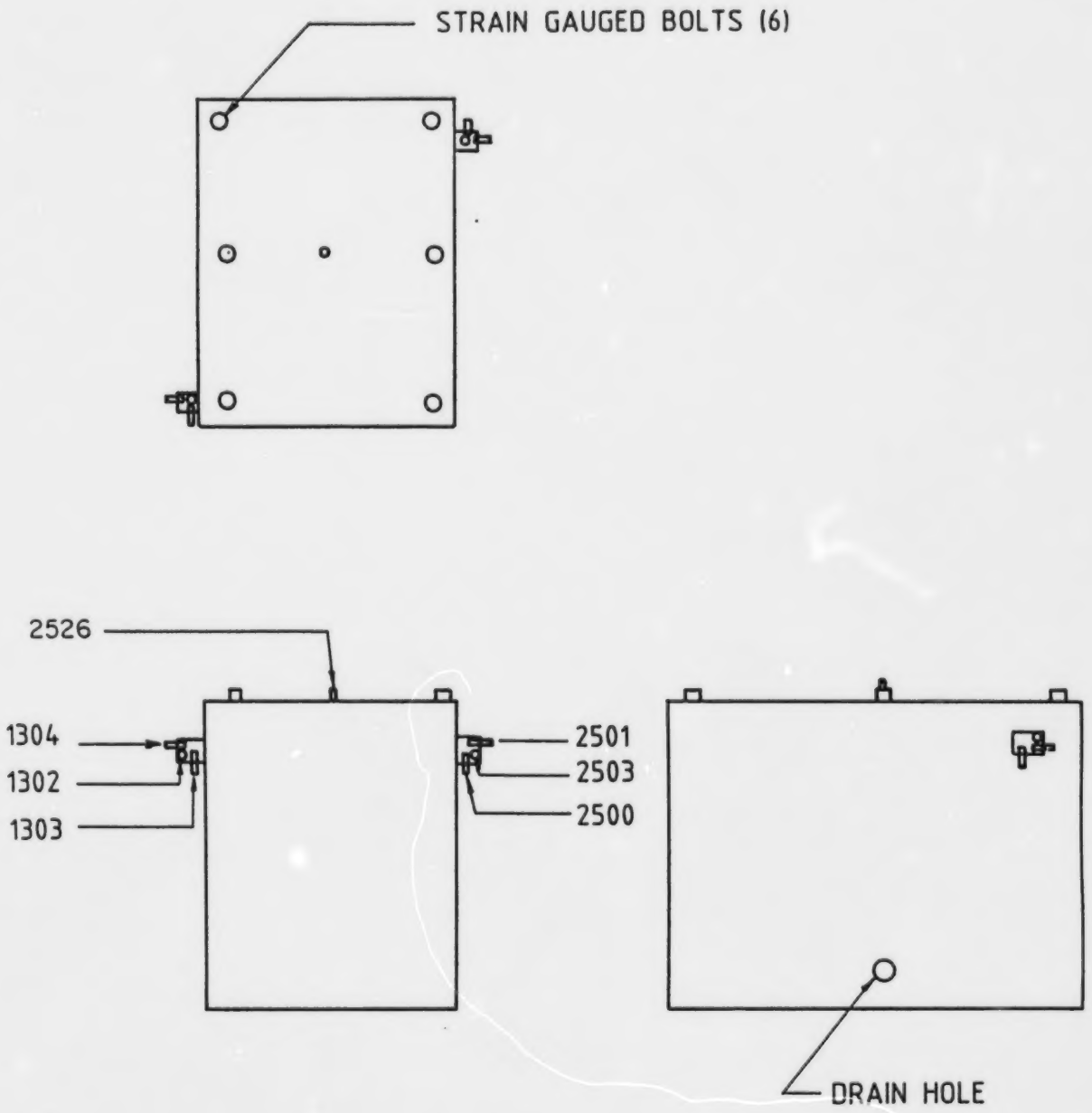

FIGURE 4
INSTRUMENT PLACEMENT ON HALF SCALE MODEL

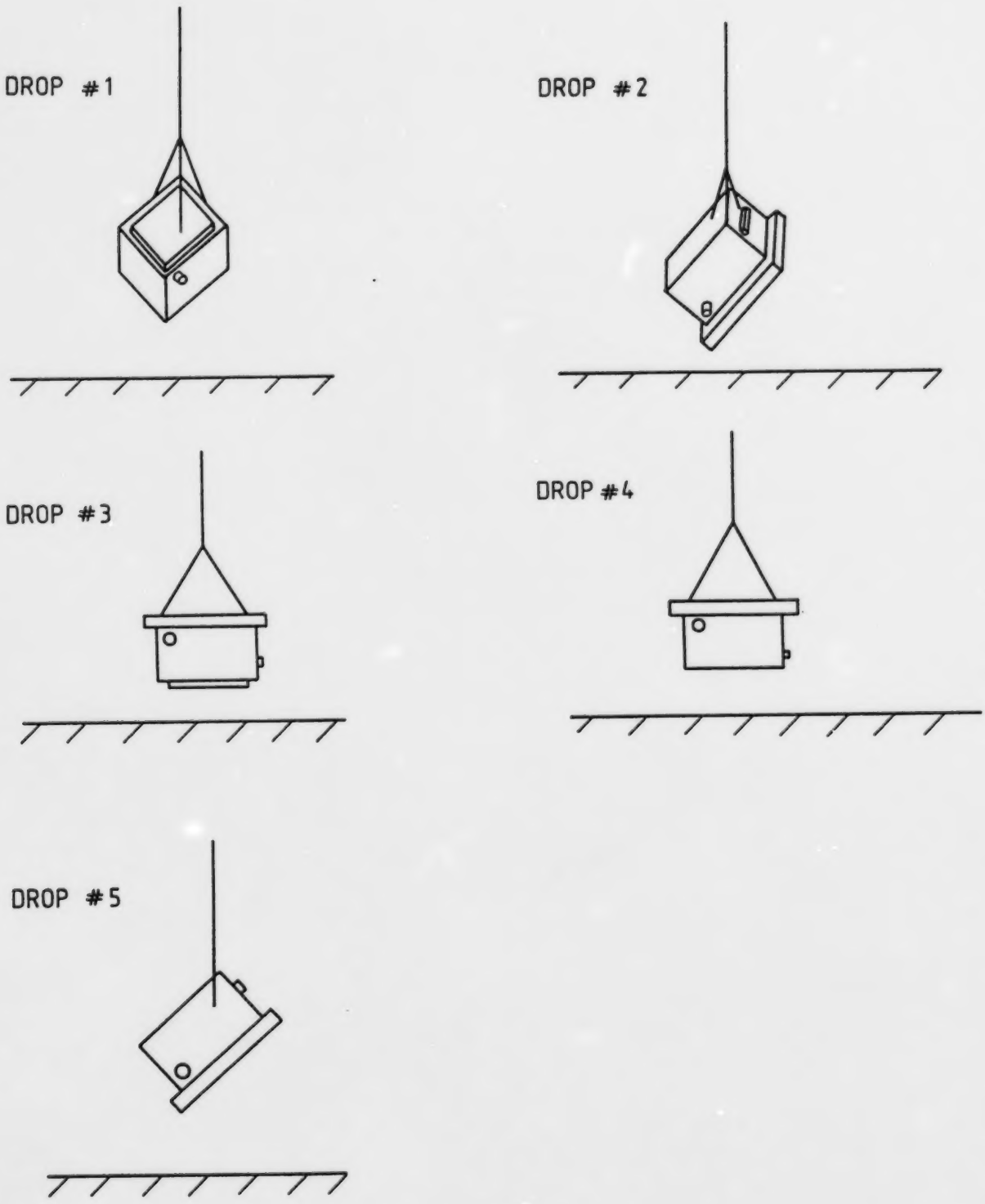

FIGURE 5
DROP ORIENTATIONS FOR SEVENTH SCALE TESTS
(SEPTEMBER, 1985)

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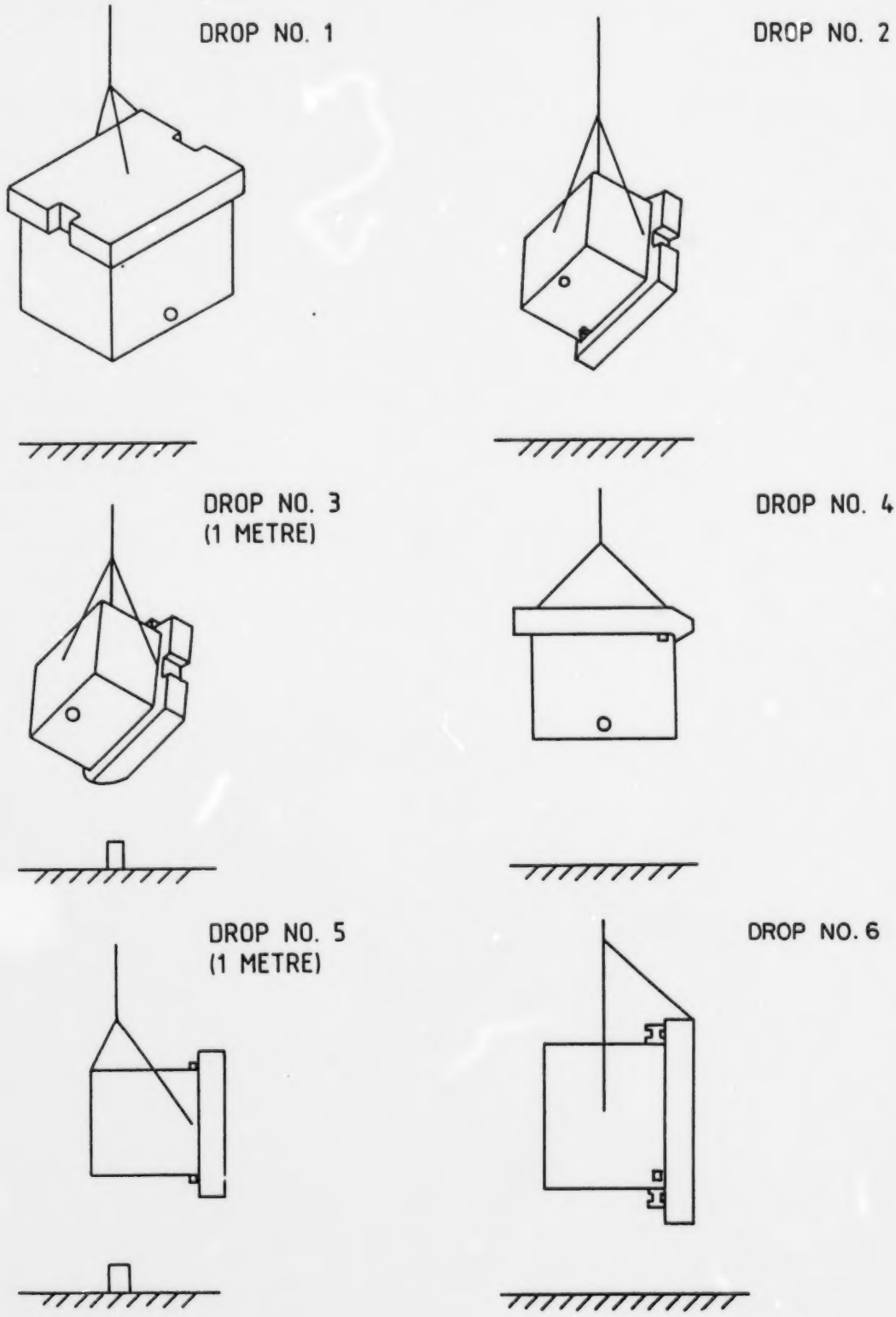

FIGURE 6
DROP ORIENTATIONS FOR HALF SCALE TESTS
(MARCH - APRIL, 1986)

88-275
178563-RD

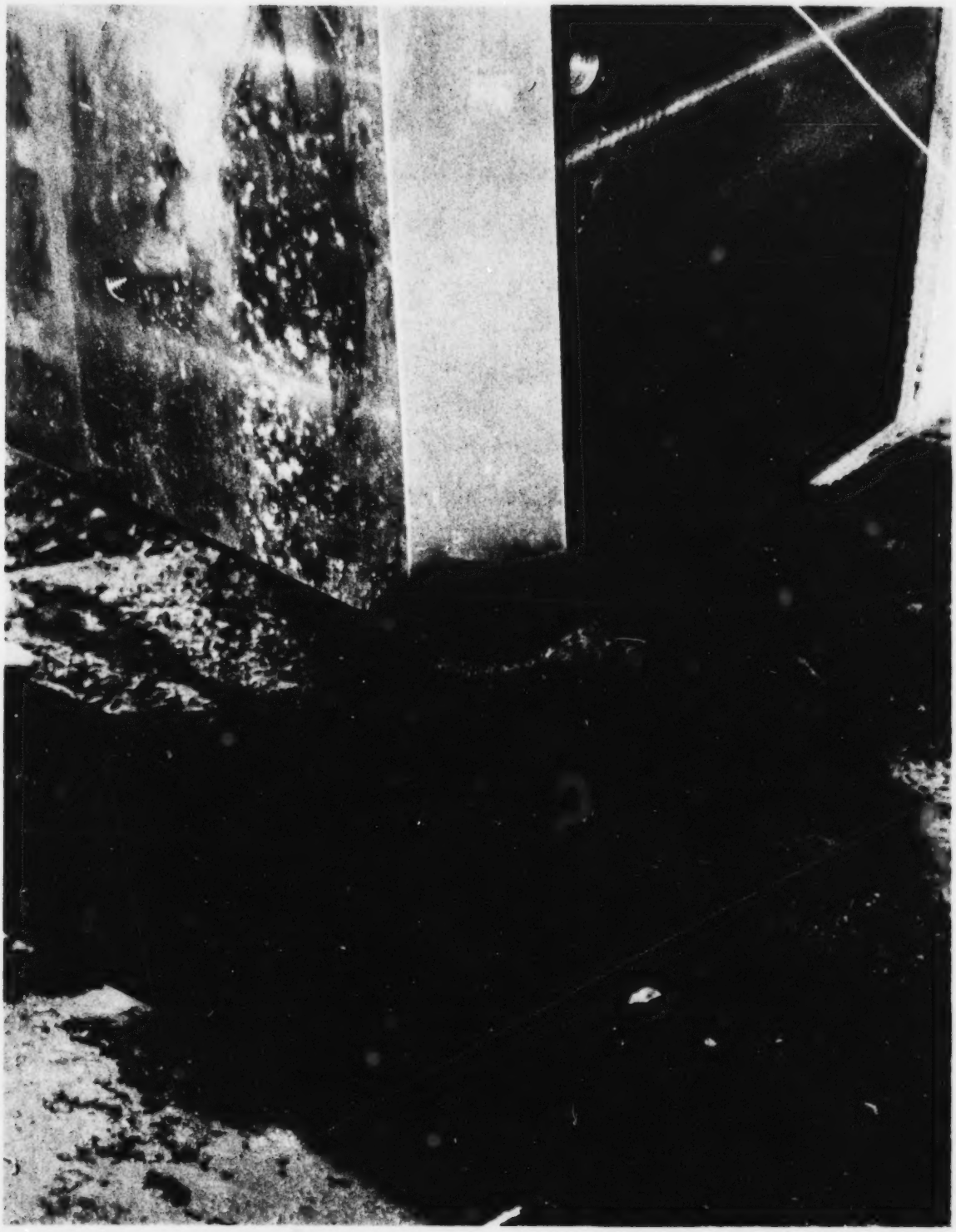

FIGURE 7

RESULTS OF BOTTOM CORNER IMPACT ON HALF SCALE MODEL

178564-RD
Bart 5 disk

FIGURE 8

PREPARATION FOR DROP 7-2, SHOWING RESULTS OF BOTTOM CORNER IMPACT ON SEVENTH SCALE MODEL

178565-RD
Bart 5 disk

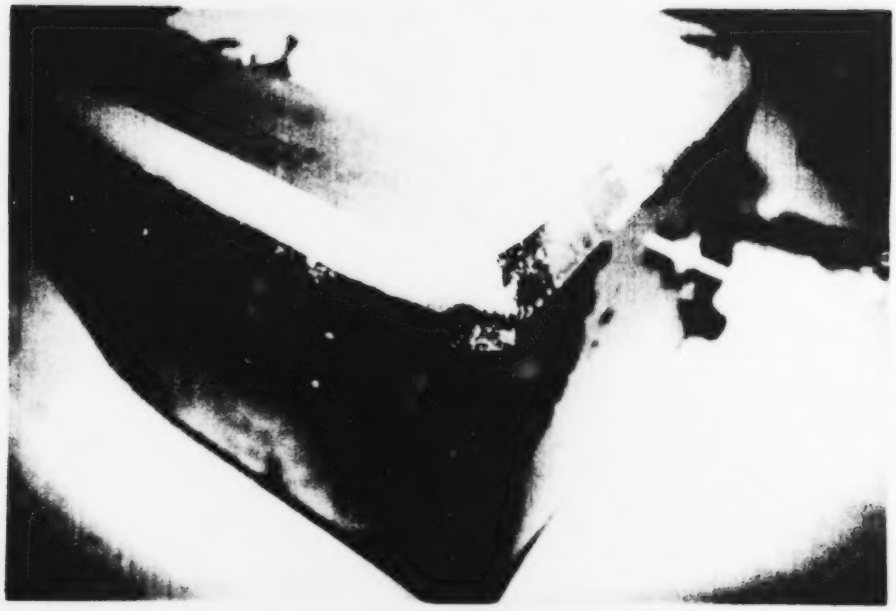

FIGURE 9

DETAIL OF DEFORMATION ON BOTTOM CORNER OF SEVENTH SCALE MODEL AFTER 9 METRE DROP

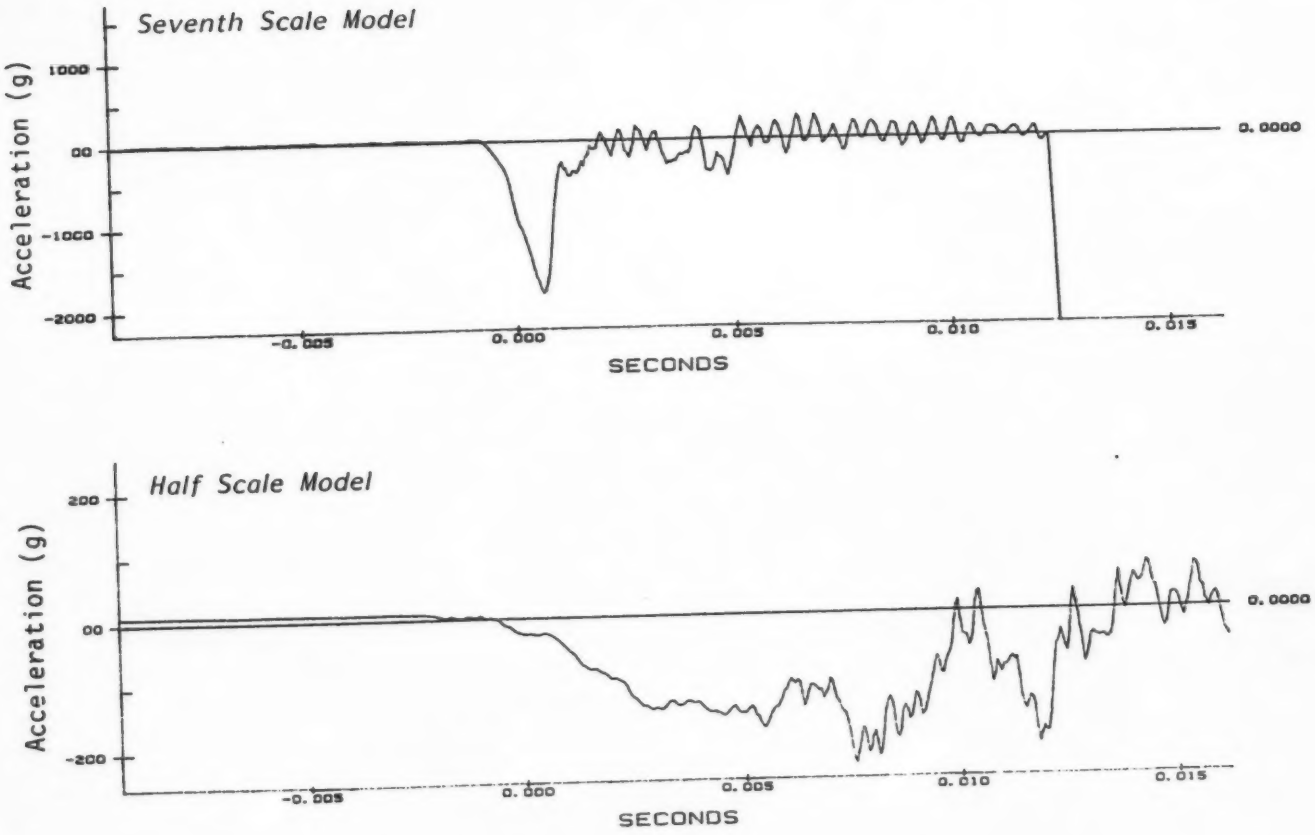

FIGURE 10

ACCELERATION HISTORIES FOR SEVENTH AND HALF SCALE MODELS
TESTS 7-1 AND 2-1, BOTTOM CORNER IMPACT VERTICAL COMPONENT

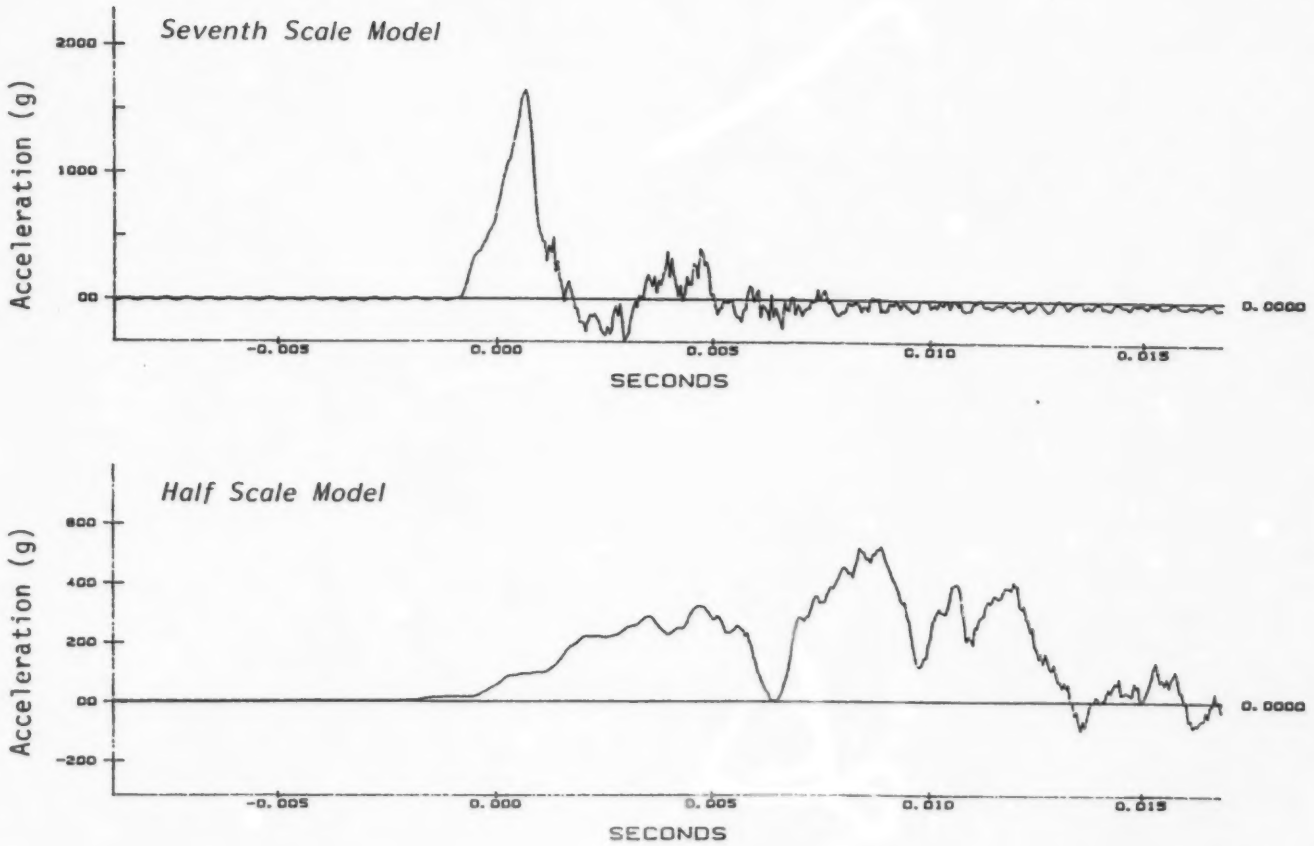

FIGURE 11

ACCELERATION HISTORIES FOR SEVENTH AND HALF SCALE MODELS
TESTS 7-1 AND 2-1, BOTTOM CORNER IMPACT LONGITUDINAL COMPONENT

88-275
173568-RD

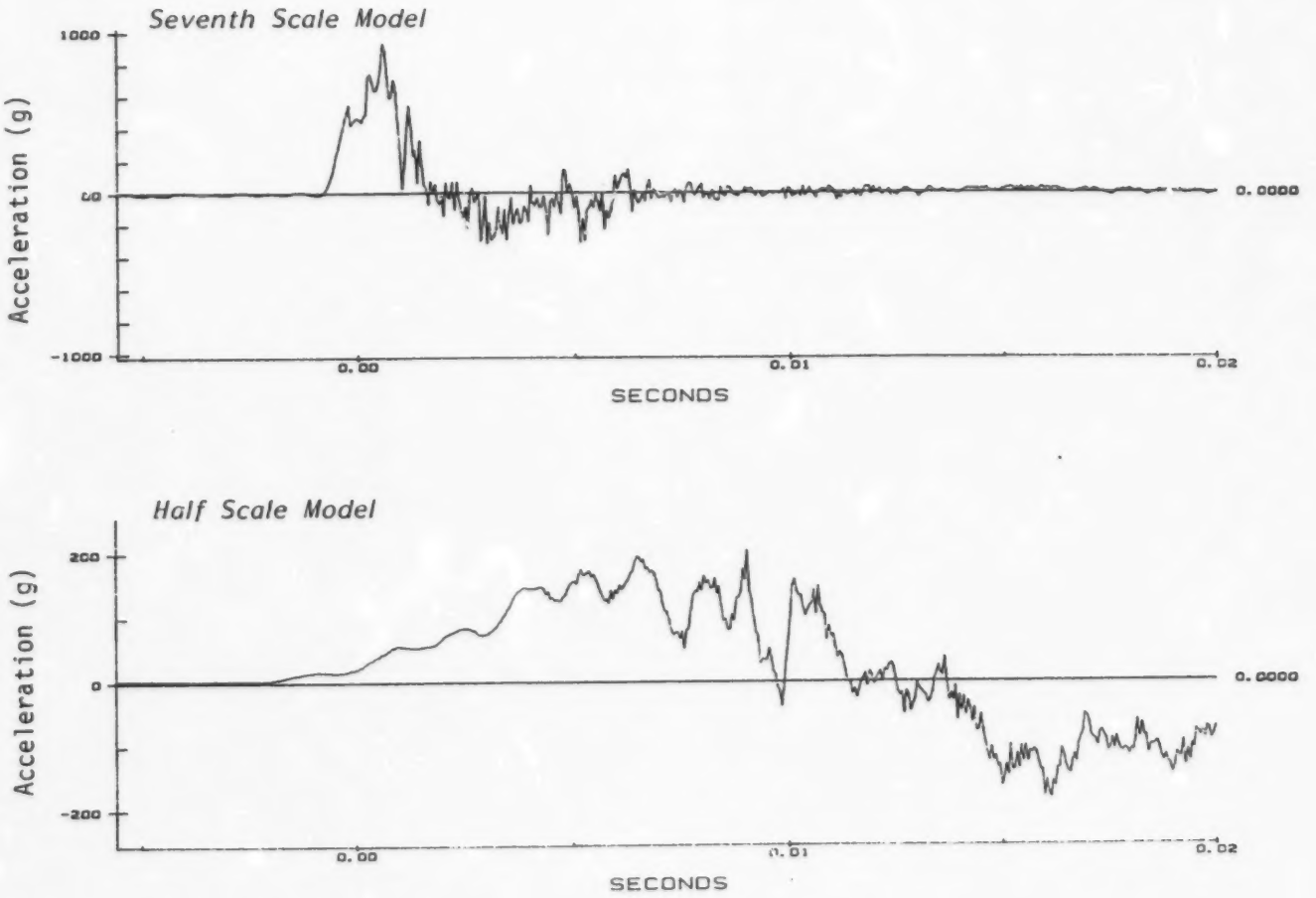

FIGURE 12

ACCELERATION HISTORIES FOR SEVENTH AND HALF SCALE MODELS
TESTS 7-1 AND 2-1, BOTTOM CORNER IMPACT TRANSVERSE COMPONENT

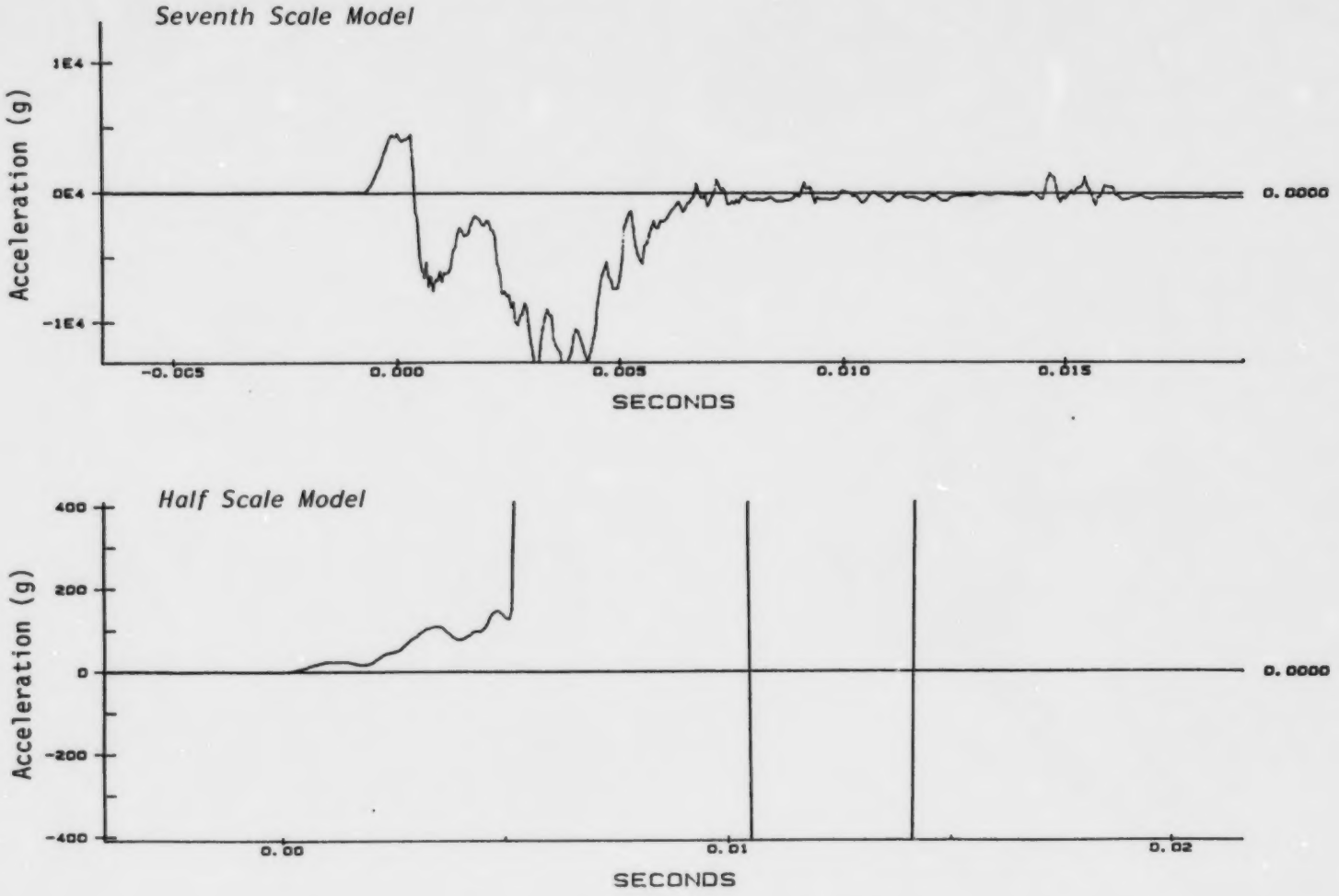

FIGURE 13

ACCELERATION HISTORIES FOR SEVENTH AND HALF SCALE MODELS
TESTS 7-1 AND 2-1, BOTTOM CORNER IMPACT,
LID ACCELEROMETERS (VERTICAL)

FIGURE 14

IMPACT LIMITER FROM SEVENTH SCALE MODEL SHOWING RESULTS OF TOP DROP TEST CORNER

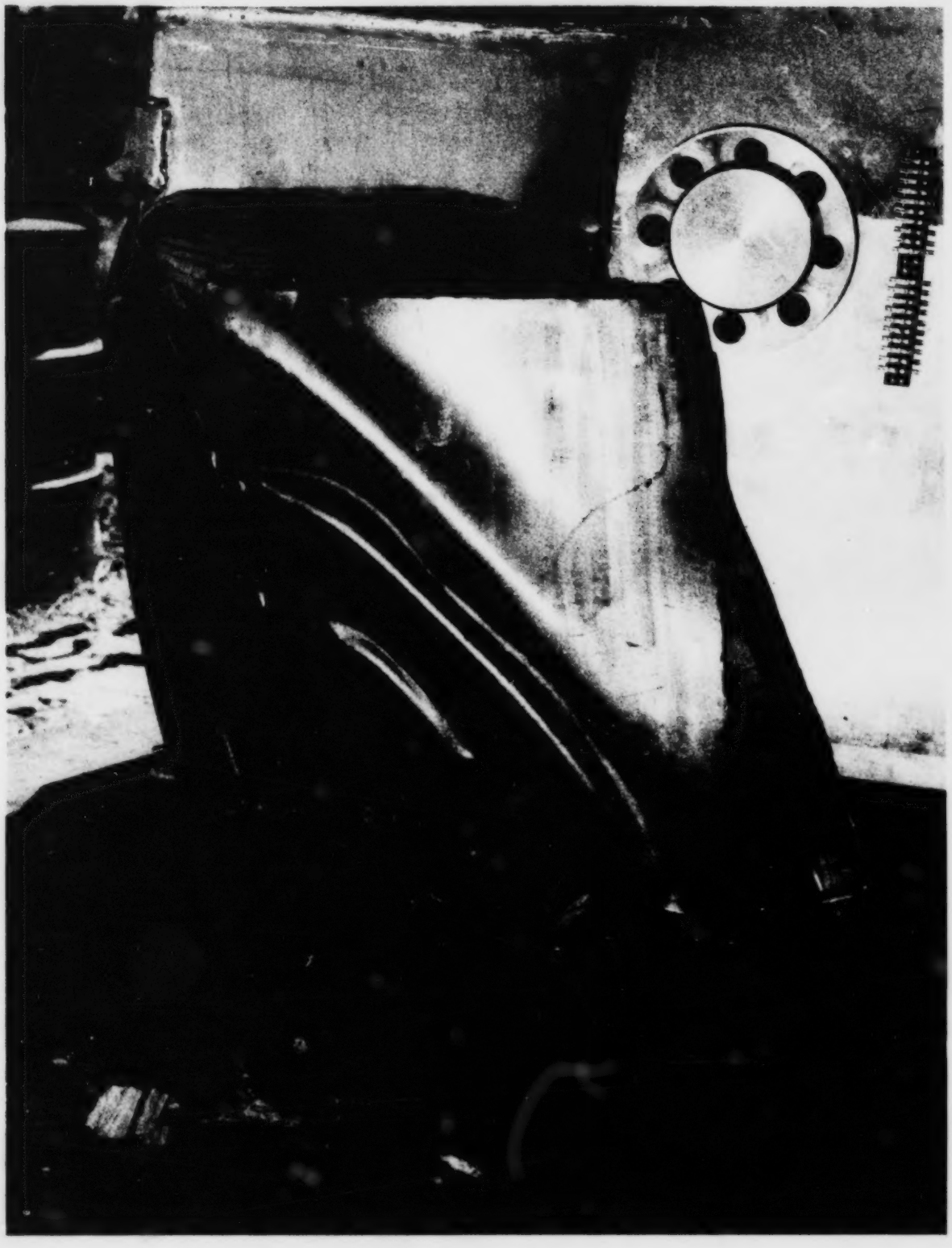

FIGURE 15

DAMAGE TO HALF SCALE LIMITER AFTER TOP CORNER DROP TEST - APRIL, 1986 - NOTE SPLIT SEAMS DUE TO INADEQUATE WELDS

178571-RD
Bart 5 disk

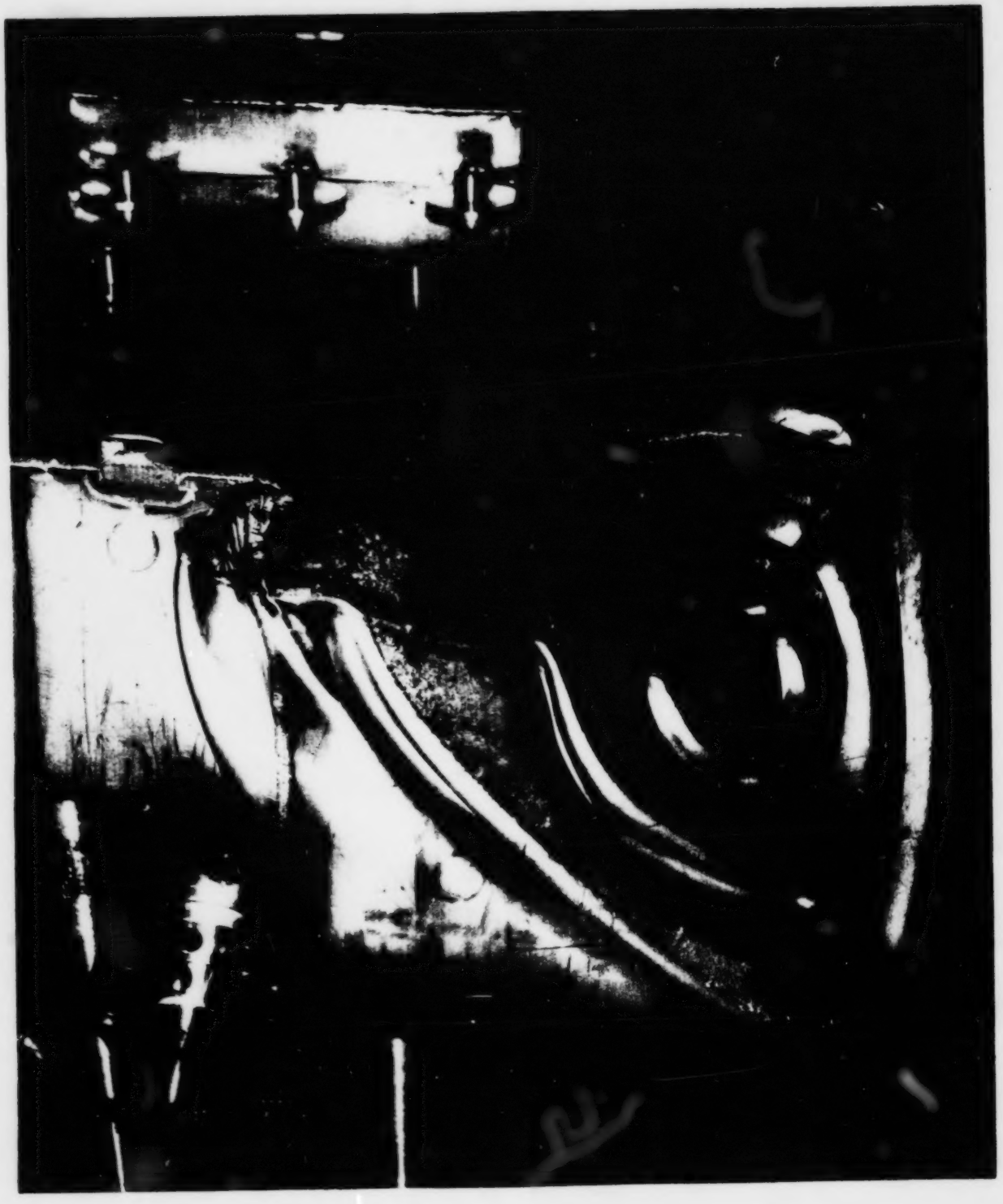

FIGURE 16

DAMAGE TO HALF SCALE LIMITER FROM TOP CORNER DROP TEST - MAY, 1986 (RE: TEST WITH BETTER QUALITY WELDING)

178572-RD
Bart 5 disk

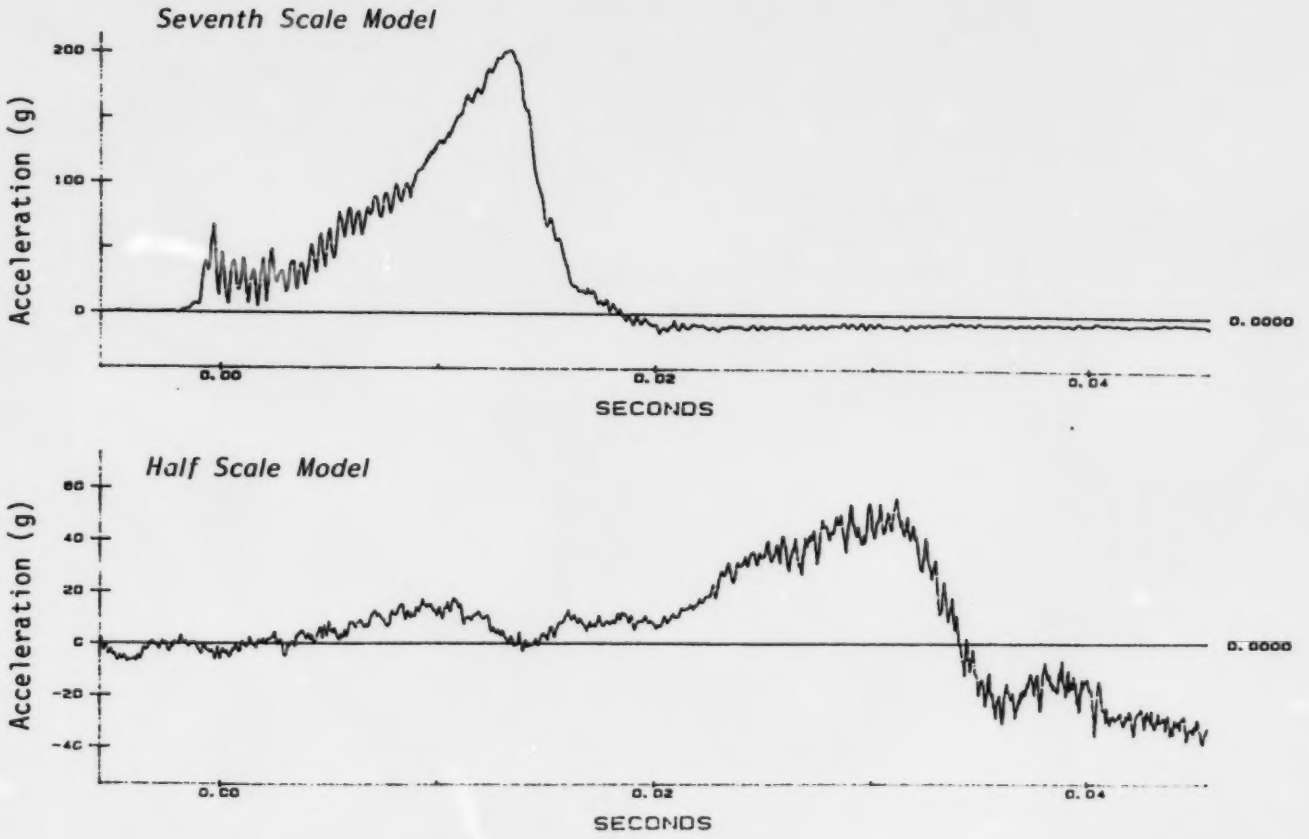

FIGURE 17

ACCELERATION HISTORIES FOR SEVENTH AND HALF SCALE MODELS
TESTS 7-2 AND 2-2, TOP CORNER IMPACT VERTICAL COMPONENT

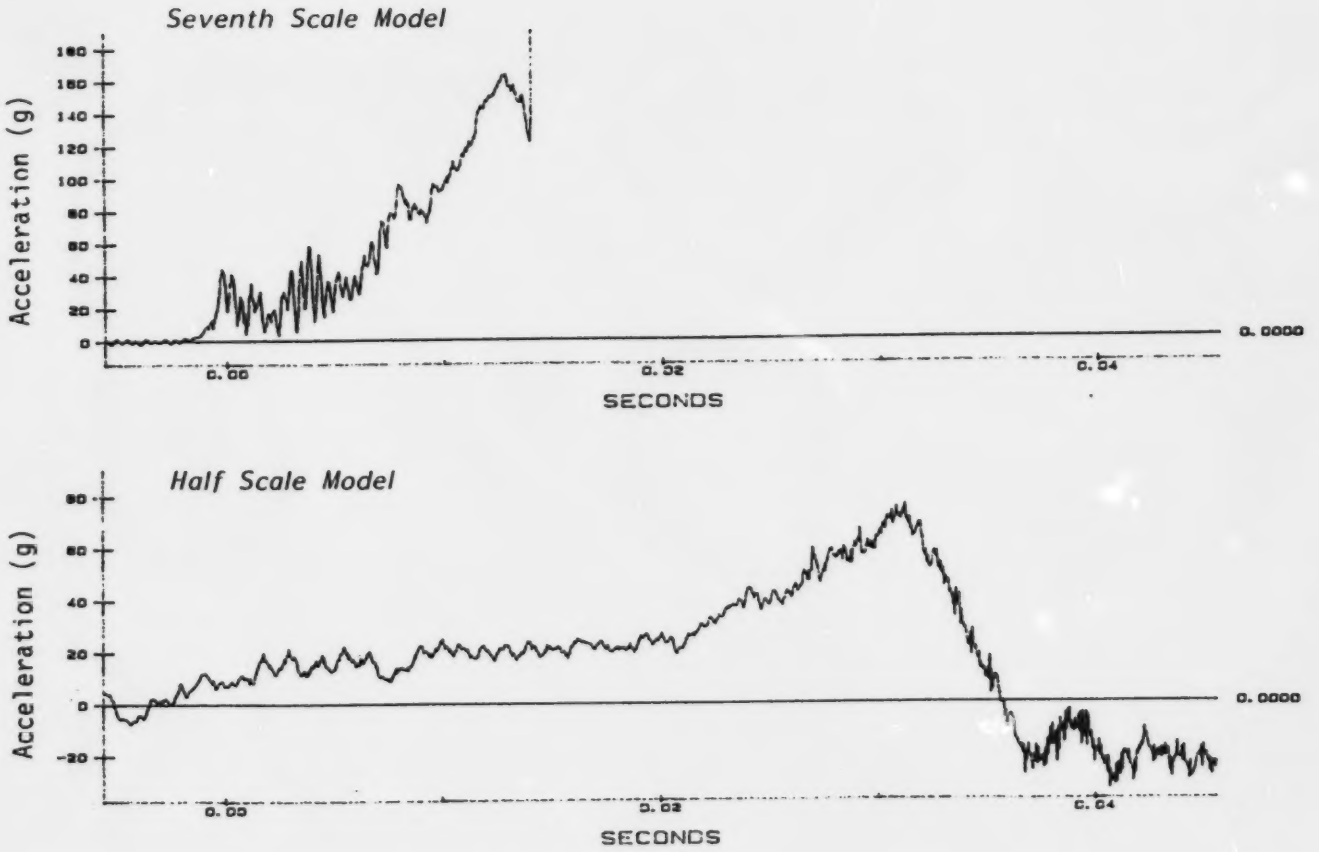

FIGURE 18

ACCELERATION HISTORIES FOR SEVENTH AND HALF SCALE MODELS
DROPS 7-2 AND 2-2, TOP CORNER IMPACT LONGITUDINAL COMPONENT

88-275
178574-RD

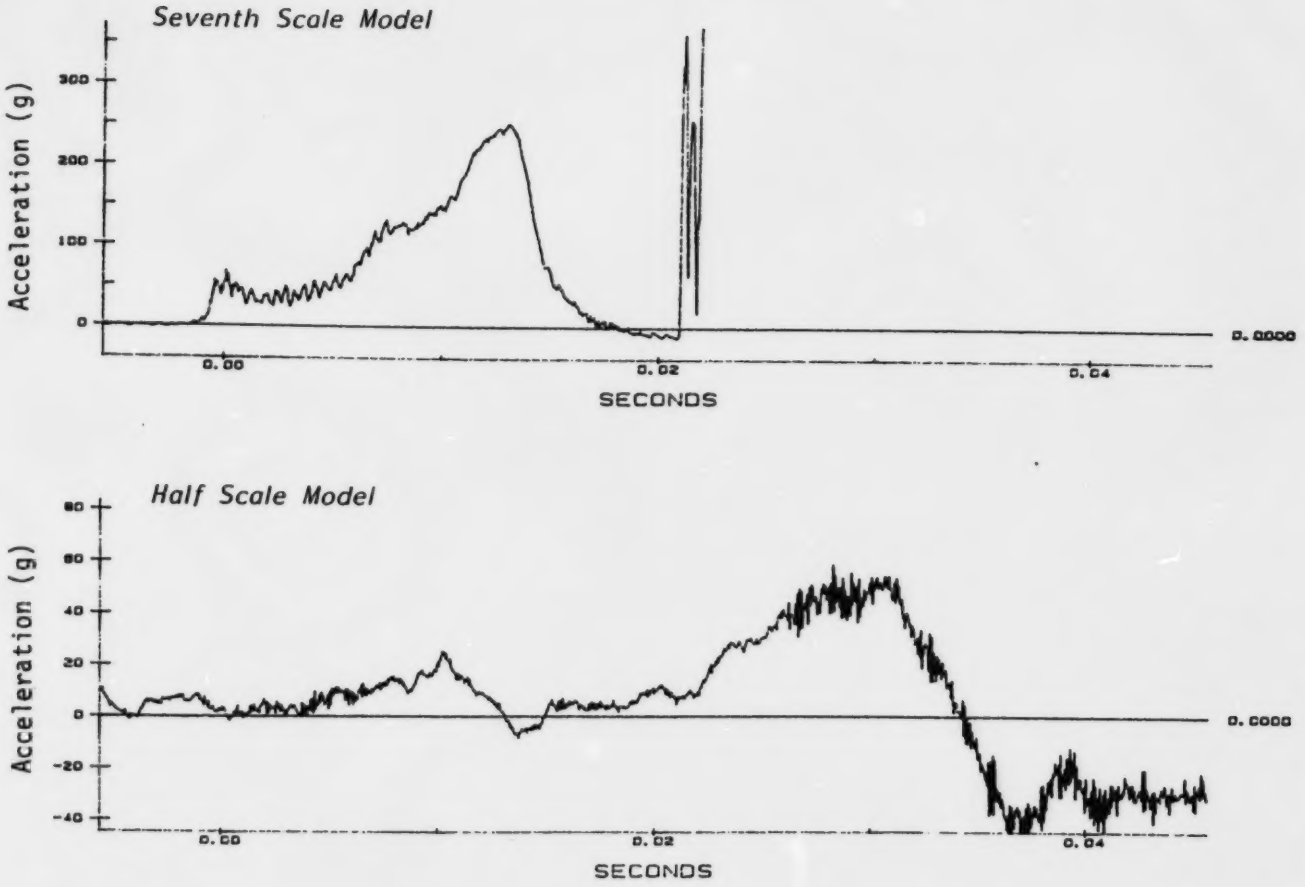

FIGURE 19

ACCELERATION HISTORIES FOR SEVENTH AND HALF SCALE MODELS
TESTS 7-2 AND 2-2, TOP CORNER IMPACT TRANSVERSE COMPONENT

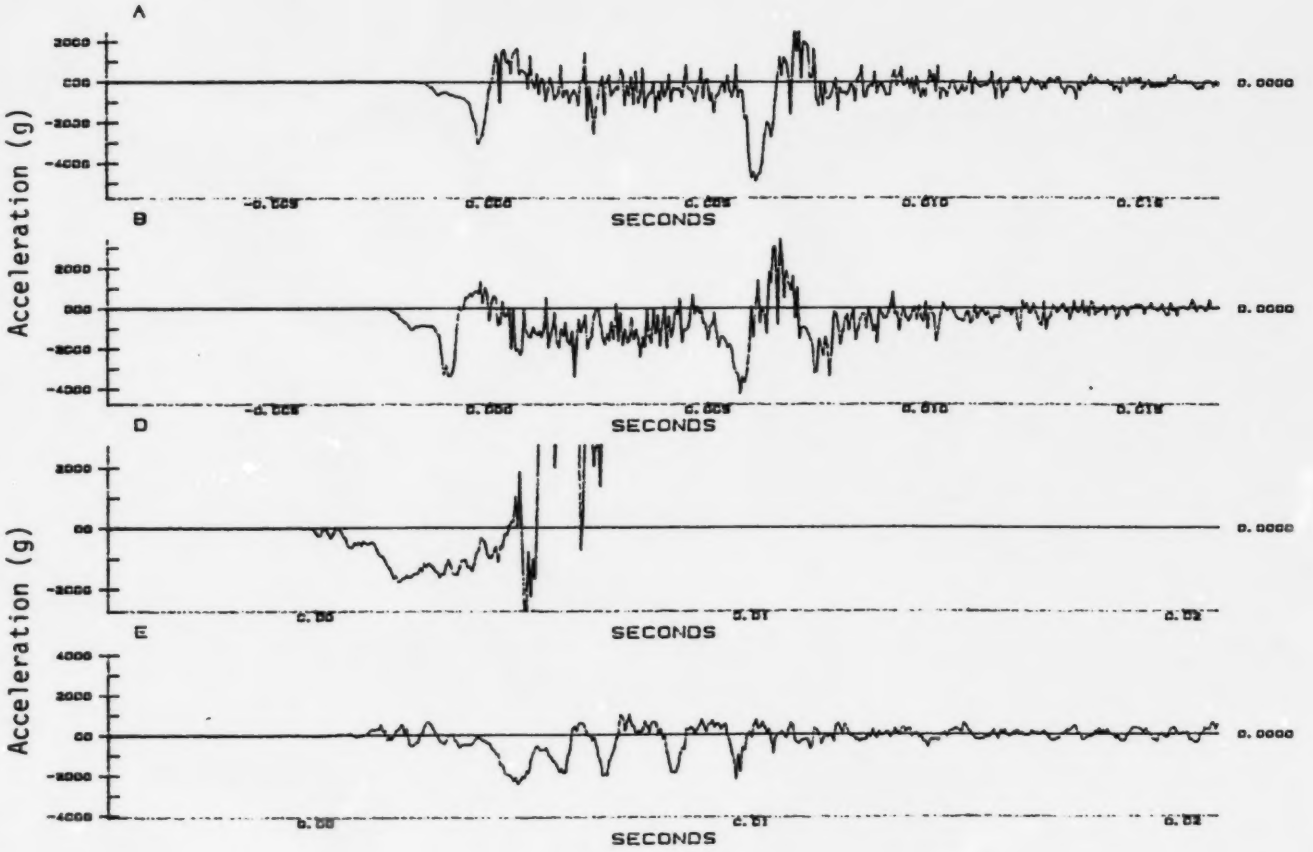

FIGURE 20

ACCELERATION HISTORIES FOR SEVENTH AND HALF SCALE MODELS
TESTS 7-4 AND 2-4, FLAT BOTTOM IMPACT VERTICAL COMPONENT

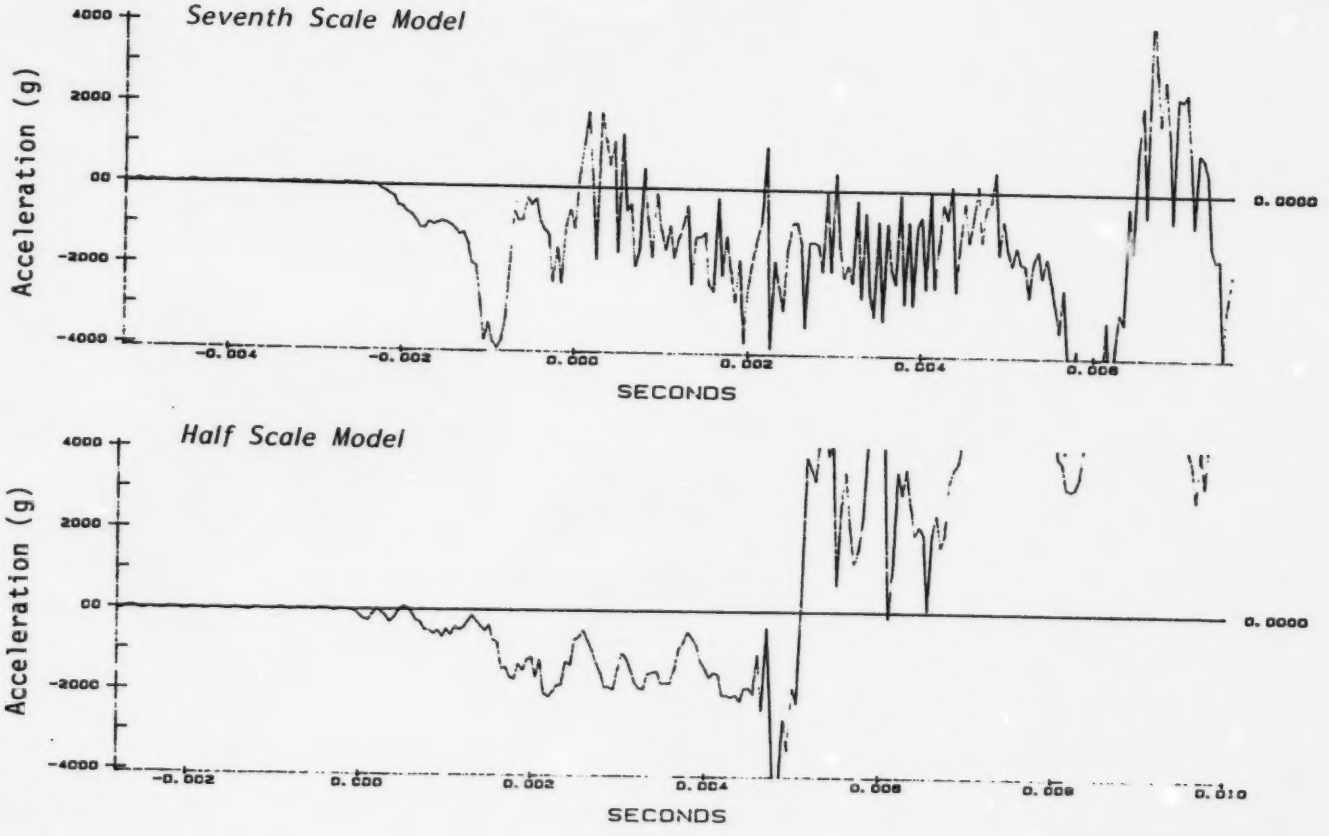

FIGURE 21
AVERAGED ACCELERATION HISTORIES FOR SEVENTH AND HALF SCALE MODELS
TESTS 7-4 AND 2-4, FLAT BOTTOM DROP VERTICAL COMPONENT

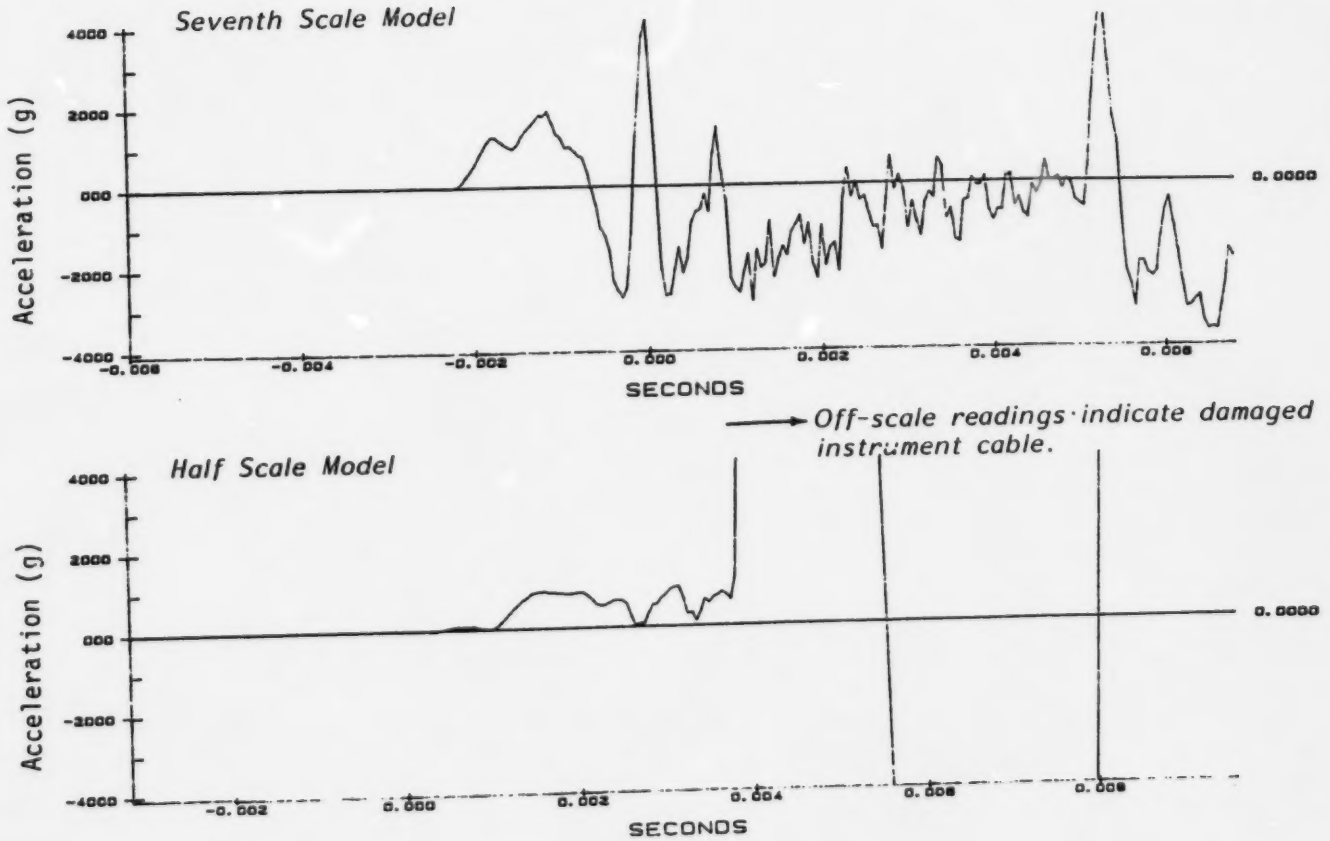

FIGURE 22

ACCELERATION HISTORIES FROM LID-MOUNTED ACCELEROMETERS
TESTS 7-4 AND 2-4, FLAT BOTTOM DROP

APPENDIX A

SCALING OF IMPACT MECHANICS

It is common in many areas of engineering to use tests on reduced scale models for predicting the behaviour of structures or systems that are too large or too expensive to test in full scale. The ideas that small replicas can standard in for full scale prototypes is intuitively very appealing, but it is important to ensure that all relevant system parameters are properly scaled.

The theoretical basis for using scale models is Buckingham's π (Pi) theorem. This theorem states that if the behaviour of a system depends on N variables (force, stress, time, material properties, size, etc.), where these variables have units that can be expressed as a combination of M fundamental dimensions (e.g. length, mass and time), then the system can be described in terms of a set of N-M non-dimensional parameters. Thus, if some "response" of the system can be represented as a function of N variables x_i:

$$f(x_1, x_2, x_3, \ldots x_N)$$

then an equivalent description can be written as:

$$\Phi(\pi_1, \pi_2, \pi_3, \ldots \pi_n)$$

where π_i are non-dimensional parameters and $n = N-M$. The functions f() and $\Phi()$ could be extremely complex. Nevertheless, the behaviour of the system would stay the same even though the units used to define the variables are changed.

The important implications of this theorem is that a scale model would reproduce the behaviour of the original, **provided all of the non-dimensional parameters stay the same.**

As an example, consider a system that can be described in terms of the thirteen variables listed below (the list of kept short for clarity).

Variable	Quantity	Units
d	displacement	L
x	space co-ordinate	L
l	linear dimension	L
t	time	T
m	mass	M
v	velocity	L/T
a	acceleration	L/T^2
F	force	ML/T^2
e	energy	ML^2/T^2
σ	stress	M/LT^2
σ_y	yield stress	M/LT^2
E	Young's modulus	M/LT^2
ρ	density	M/L^3

A complete set of non-dimensional parameters incorporating these variables is:

π_1	d/l
π_2	x/l
π_3	vt/l
π_4	at^2/l
π_5	F/ma
π_6	$e/\sigma l^3$
π_7	$\rho l^3/m$
π_8	σ/E
π_9	σ_y/E
π_{10}	$\sigma/\rho v^2$

According to scaling theory, the response of a scale model (subscript m) would be equivalent to the response of a full-scale "prototype" (subscript p) if all of the π parameters are the same.

If the model is an "s" scale geometric replica of the prototype,

$$l_m = s.l_p$$
$$x_m = s.x_p$$

and parameter π_2 is preserved in the model.

If the same material is used for the model and the prototype, then π_7, π_8, and π_9 are also preserved. π_6 will remain constant if the energy density is the same in the model and in the prototype. To keep π_{10} constant, it is necessary for velocities to be the same for model and prototype. The same logic can be applied to all other variables, with the result:

d_m	=	$s.d_p$	
x_m	=	$s.x_p$	
t_m	=	$s.t_p$	
m_m	=	$s^3.m_p$	
v_m	=	v_p	
a_m	=	a_p/s	
e_m	=	$s^3.e_p$	
F_m	=	$s^2.F_p$	
σ_m	=	σ_p	(for elastic *and* plastic stresses)
Em	=	Ep	
ρ_m	=	ρ_p	

There are several important implications of this analysis for impact tests:

- Impact velocities must be the same for the model and the prototype. Thus, the same drop height should be used, regardless of scale model.
- Because time is scaled by a factor of s, the duration of the impact will be shorter for small scale models.
- Accelerations scale by a factor of 1/s and will be higher for small scale models.
- Stresses and strains are identical for the model and the prototype, but time is scaled. Thus, strain rates will be higher in a small scale model. This means that model behaviour is not completely scalable when material properties are highly strain-rate dependant.[1]
- Ideally, the model would be a scaled geometric replica of the prototype. This may be very difficult to achieve in practice, due to manufacturing tolerances.
- Ideal modelling would also scale the intrinsic "granularity" of materials (e.g. aggregate size in concrete, grain size in wood or metal). This may be impossible to achieve, or might alter other material properties.

In summary, scale model testing can provide a reliable prediction of the behaviour of a large system. It will reproduce dynamic behaviour, but may produce misleading results if the materials in question are highly strain-rate sensitive at the loading rates being tested. The model should ideally be a very accurate replica of the full scale prototype, and care should be taken to ensure that fabrication tolerances and simplifications have a negligible effect on system response. Scale modelling obviously becomes trickier and the results less reliable as scaling becomes more extreme.

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1. If strain rate has an important influence on material behaviour, then theory requires that it should appear as one of the variables in the function f(). There would then be a non-dimensional π parameter that incorporates strain rate in the $\Phi()$ relationship. However, it may prove to be impossible to keep this parameter constant through a scale change.